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CALCULATIONS OF COMBINED HEAT AND VAPOUR TRANSPORT THROUGH CLOTHING SYSTEMS: APPLICATION TO WATER-VAPOUR-PERMEABLE RAINWEAR.

by

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ABSTRACT

A numerical model has been developed to calculate the combined heat and vapour flow, at steady state, through multilayer clothing systems including heat transfer by radiation and the condensation of water vapour within the clothing system. The model has been applied to a comparison of the heat stress and water accumulation expected in rainwear made of completely impermeable material and of a water-vapour-permeable laminate, when the wearer works hard enough to promote sweating. The results indicate significant advantages can be expected from the permeable rainsuit.

RÉSUMÉ

On a mis au point une modèle mathematique à fin de calculer le taux d'éculement combiné de chaleur et de vapeur, y compris le transfert thermique par rayonnement et par condensation. A favers les systemes de vêtements à couches multiples dans un régime per manent.

On a servi de cette modèle pour fairé une étude comparative des caracteristiques calculeés du stress d'echauffement et de l'accumulation d'eau entre les vêtements de pluie fabriqués en tissu imperméable à la vapeur et de ceux fabriqués en tissu perméable à la vapeur.

Les resultats montrent que les vêtements de pluie en tissu perméable à la vapeur offrent de grands avantages.

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INTRODUCTION

One of the most important problems in protection a soldier from the natural environment is the need to get rid of moisture when he is working hard and sweating. In any environment the accumulation of sweat within the clothing may be uncomfortable but in a cold Arctic environment the resulting degradation of the thermal insulation of the clothing may present a serious hazard.

In order to design and evaluate clothing systems intelligently, it is necessary to understand the propagation of heat and vapour through combinations of layers of different fabrics. In situations where there is no condensation or absorption of water vapour, the characterization of the heat and vapour flow properties of the system is straightforward since the two types of flow are independent; each layer of fabric or trapped air will have a thermal resistance and a vapour resistance and *these simply add to give the overall thermal resistance and overall vapour* resistance. However, where water condenses or is absorbed, latent heat is liberated and the flow of heat and vapour become inter-related thus making the simple picture inadequate.

A long-term project has been initiated to study, in detail, combined heat and water vapour flow, particularly but not exclusively, in Arctic clothing systems. Three principal means of study are to be employed concurrently: computer simulations of the body and clothing systems, tests on laboratory models of the body and clothing systems, and tests on human subjects wearing the clothing and working under controlled laboratory conditions.

This paper describes the first phase of the development of a computer model which will facilitate the interpretation of experimental results and provide a guide to clothing design work. Part I describes the currently accepted model of heat transfer. This model is then modified to include heat transfer by radiation and to include the case where water vapour condenses within the clothing system. At this stage of the study, convection is completely ignored and the treatment of radiation is simplistic so that the model is limited in its applicability. However, the theory is adequate to treat a limited class of problems and the calculations for one of these are presented in Part II. This is a comparison of two rainsuits, one made of an impermeable materials and the second of the vapour-permeable but waterproof fabric "Gore-tex" (1).

PART I - COMBINED HEAT AND VAPOUR TRANSPORT THROUGH CLOTHING SYSTEMS

BASIC ASSUMPTIONS

Researchers have traditionally characterized the propagation of heat through a clothing system by:

$$(1) \quad Q = \frac{1}{R_H} (T_1 - T_0)$$

where Q is the heat flow per unit area

R_H is the total thermal resistance

T_0 is the skin temperature

and T_1 is the outside ambient temperature

and similarily for the water vapour flow:

$$(2) \quad m = \frac{1}{R_V} (P_1 - P_0)$$

where m is the mass flow per unit area

R_V is the total vapour resistance

P_0 is the vapour pressure at the skin

and P_1 is the outside ambient vapour pressure

The total loss of heat Q_T from the skin surface is then:

$$(3) \quad Q_T = Q + Hm$$

where H is the enthalpy of vaporization of the water.

Radiation and convection have been normally ignored or taken to be implicit in the measurement of the thermal resistance R_H.

Also implicit in equations 1 and 2 is the assumption that no evaporation or condensation of water takes place within the clothing layers; evaporation occurs only at the skin. In these circumstances, the quantities Q and m are constants, independent of position within the clothing.

In this present study, the foregoing assumption is relaxed and condensation is allowed. Heat which is carried as latent heat of vaporization near to the skin may be liberated at some point within the clothing layers where the water condenses and then travels to the outer layer by conduction or as radiation. Thus Q and m are no longer constants and equations 1 and 2 are not valid but must be replaced by differential equations that describe the heat and vapour flow at each point within the clothing layers. These differential equations must be solved simultaneously, with appropriate boundary conditions, to give the total heat and vapour propagation.

The conditions under which the proposed model is valid are summarized below. They differ from the customary set of conditions mainly in that condensation is allowed and that radiation is explicitly treated rather than being included in the evaluation of thermal resistance for each fabric, but the presence of liquid water or ice within the system requires the addition of constraint (c) below.

a) The system is in steady state.
b) Heat is transferred by conduction, radiation or the diffusion of water vapour: free and forced convection and the motion of liquid water by wicking are excluded.
c) At any point within the clothing system the thermal conductivity and vapour permeability are independent of temperature, humidity and the presence of liquid water or of ice.
d) Each layer of clothing is either perfectly transmitting or perfectly absorbing to thermal radiation.
e) Each clothing layer has uniform thickness and does not vary in its physical properties in any direction parallel to the surface of the skin.
f) The width of each layer and the radius of curvature of any portion are much larger than the thickness so that both the finite extent and the curvature may be ignored.

These restrictions are, to a certain extent, unrealistic, particularly (b) but the complexity of the full problem including all possible heat flow methods would be prohibitive. In addition, (a) and (c) are impossible. If water is accumulating in the clothing system it cannot truly be in steady state and this accumulation will inevitably degrade the insulating value of the materials. Nevertheless, these initial calculations may still be of use for a time sufficiently long after the onset of sweating to establish approximately steady conditions but before water build up becomes significant.

BASIC EQUATIONS

Consider within a clothing system a thin slice of clothing, of unit area and thickness dx, at a distance x from the skin, as illustrated in Figure 1.

Let $T(x)$ = temperature at point x
$P(x)$ = water vapour pressure at point x
$k_H(x)$ = thermal conductivity at point x
$k_v(x)$ = vapour conductivity at point x
$Q(x)$ = rate of flow of heat by conduction per unit area
$m(x)$ = rate of flow of vapour per unit area
$m_c(x)$ = rate of condensation of vapour per unit volume
$Q_c(x)$ = rate of liberation of heat per unit volume due to the condensation of water.
$Q_R(x)$ = rate of liberation of heat per unit volume due to the absorption of thermal radiation.

The flow of heat by conduction is given by:

$$(4) \quad Q(x) = -k_H(x)\frac{dT(x)}{dx}$$

and the flow of moisture by:

$$(5) \quad m(x) = -k_v(x)\frac{dP(x)}{dx}$$

Conservation of energy requires that the flow of heat into the volume element at x be equal to the flow outward.

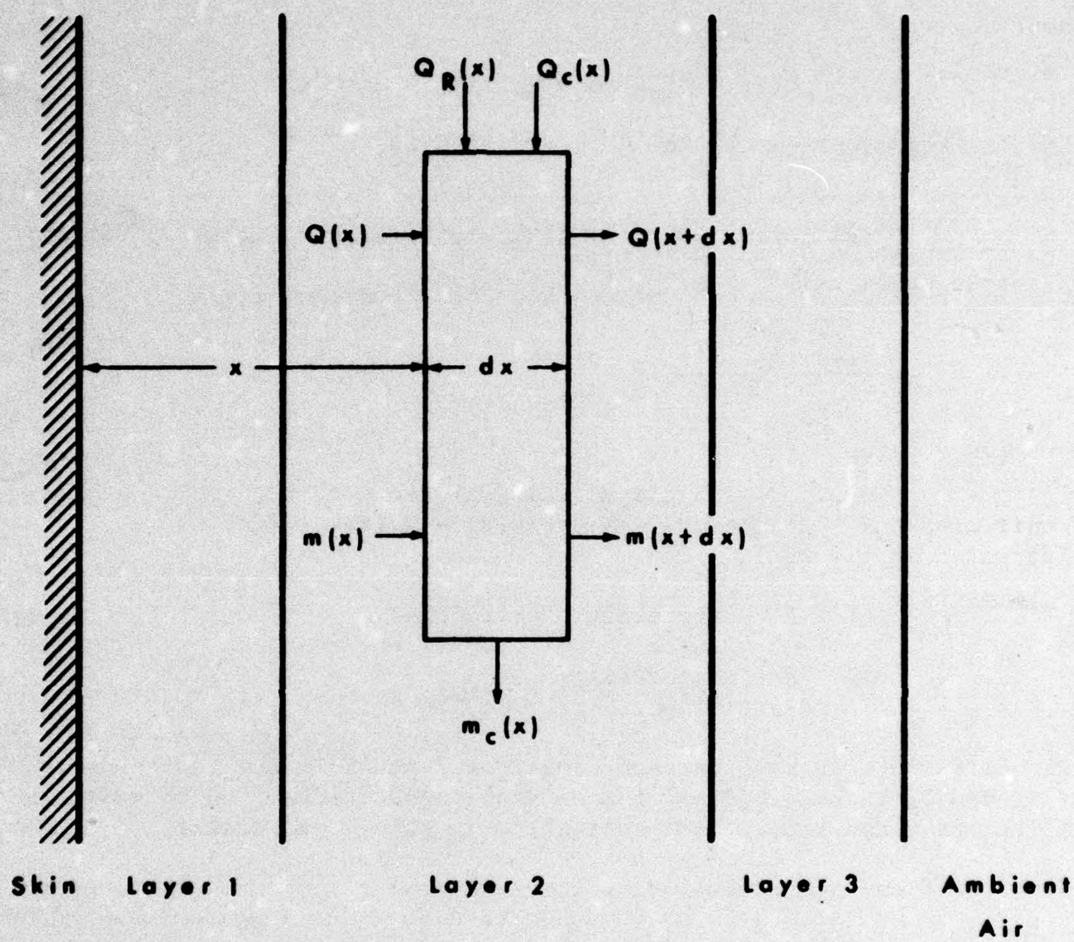

Figure 1. Schematic representation of heat and vapour flow into and out of a volume element within the clothing layers.

Thus:

$$(6) \quad Q(x) + Q_C(x)dx + Q_R(x)dx = Q(x+dx)$$

substituting equation (4) for Q in equation 6:

$$(7) \quad -k_H(x)\frac{dT}{dx}(x) + Q_C(x)dx + Q_R(x)dx = -k_H(x+dx)\frac{dT}{dx}(x+dx)$$

Dividing through by dx and noting that for a function f(x);

$$\frac{f(x+dx) - f(x)}{dx} = \frac{df(x)}{dx}$$

equation 7 reduces to:

$$(8) \quad \frac{d}{dx}\left[k_H(x)\frac{dT(x)}{dx}\right] = -Q_C(x) - Q_R(x)$$

A similar analysis of the vapour flow yields:

$$(9) \quad \frac{d}{dx}\left[k_V(x)\frac{dP(x)}{dx}\right] = m_C(x)$$

(The difference in sign between equations 8 and 9 is due to the definition of Q_C and Q_R as heat "gains" but m_C as a vapour "loss." With this definition Q and m will both normally be positive quantities.)

Equations 8 and 9 are coupled by the relation;

$$(10) \quad Q_C(x) = H\, m_C(x)$$

where H is the enthalpy of vapourization of water.

Since it is assumed that each layer of clothing is either perfectly absorbing or perfectly transmitting, $Q_R(x)$ will be zero everywhere except at the boundary between an opaque and a transparent layer. The radiant heat flow will be zero inside an opaque layer and finite inside one that is transparent. If x_1 and x_2 are the positions of the two sides of a transparent layer (or a composite of several transparent layers) then the heat absorbed at x_1 is given by the Stefan-Boltzmann law:

$$\sigma T^4(x_2) - \sigma T^4(x_1)$$

and that absorbed at x_2 is the negative of this (see Figure 2).

Thus Q_R can be expressed as a series of the form:

$$(11) \quad Q_R(x) = \sum_{x_1, x_2} \sigma \{T^4(x_2) - T^4(x_1)\}\{\delta(x-x_1) - \delta(x-x_2)\}$$

where $\delta(x)$ is the Dirac Delta Function*.

Calculation of combined heat and vapour flow requires the simultaneous solutions of equation 8 to 11 with appropriate boundary conditions.

BOUNDARY CONDITIONS

If the total thickness of the clothing system, including the outermost still air layer, is D then the temperature and vapour pressure at x = D are constrained to be those of the ambient air:

$$(12) \quad T(D) = T_1$$

$$(13) \quad P(D) = P_1$$

For the purposes of calculating radiative heat transfer this outer boundary is assumed to be a perfect black body at temperature T_1. In other words the "radiative" and "kinetic" temperatures of the environment are taken to be equal.

At the skin surface, x = 0, the boundary conditions are less easily defined. The unique solution of the equations requires two pieces of information, one of which is a constraint on the temperature or heat flow, the other a constraint on the vapour pressure or vapour flow. The way in which the body regulates skin temperature and wetness is, of course, complex and variable from one set of ambient conditions and work load to another but, within a narrow set of conditions, it may well be sufficient to specify conditions as was done for the outer boundary. Since the problems of interest are usually ones involving active sweating it seems appropriate to specify:

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* Defined by $\delta(x) = 0$ for $x \neq 0$ and $\int_{-a}^{a} \delta(x) f(x)dx = f(0)$ for any function $f(x)$ and constant a.

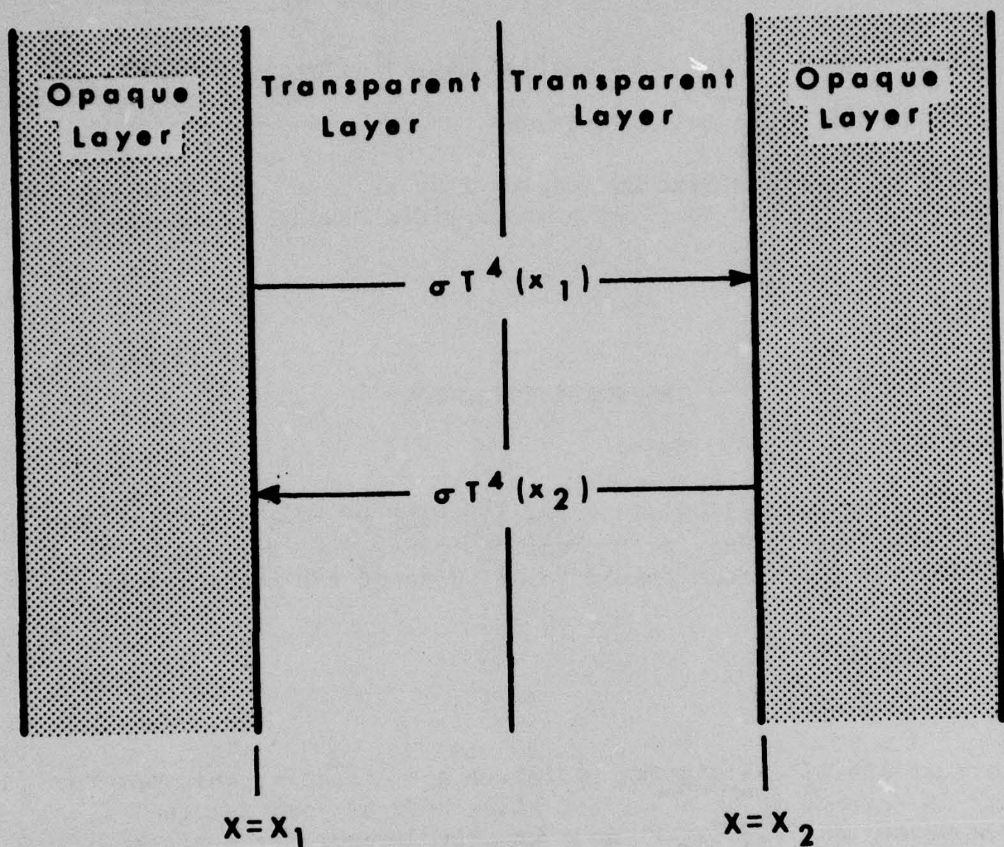

Figure 2. Radiative heat transfer across transparent layers.

(14) $T(0) = T_0 = 35°C$.

The second constraint, that on the vapour pressure or flow, may be set in one of three ways:

(i) a vapour pressure:

(15) $P(0) = P_0$

(ii) a sweat rate:

(16) $m(0) \leq \dot{m}_0$*

(iii) a total heat production rate, which indirectly specifies a vapour flow rate:

(17) $Q_T = Q(0) + Hm(0)$

The method of solution is essentially the same no matter what form the boundary conditions take and the differences in the required computer programming are minor. In all cases the skin is assumed to be a perfect black body.

METHODS OF SOLUTION

The difficulties encountered in the solution of equations 8 to 11 lie with the quantity m_c, the rate of condensation of vapour per unit volume. An expression for m_c is not readily obtainable and even if it were it would inevitably be of a form that would make the solution of the equations extremely difficult. It will, in general, be a function of: the vapour pressure, $P(x)$; the saturation water vapour pressure $P_s(x)$, which is in turn a function of temperature $T(x)$, and x directly, since it will vary from material to material. Thus,

(18) $m_c(x) = m_c(P(x), T(x); x)$

Even the simplest conceivable form of equation 18, namely:

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* The inequality is because sweat may accumulate at the skin surface.

$$(19)\quad m_c(x) = \begin{cases} 0 & \text{for } P \leq P_s \\ \alpha(x)\,\{P(x) - P_s(x)\} & \text{for } P \geq P_s \end{cases}$$

is a complicated function of P and T and so straightforward finite difference methods for the solution of differential equations are ruled out because these would require m_c to be a linear function of P and T.

An ad hoc method of solution is, however, made possible by the following observations. Whatever the exact form of m_c, its general form will be zero for $P < P_s$ and a rapidly increasing function of P for $P > P_s$. Physically this means that vapour cannot condense from air that is less than saturated but will condense very quickly from air that is supersaturated. This latter is true as long as nucleation sites are present and the fibres of a textile fabric can be expected to supply these. The effect of the rapid condensation is to limit P to not much more than P_s. Thus,

$$(20)\quad P < P_s$$

$$\text{or}\quad P \cong P_s$$

independently of the exact form of m_c.

The method of solution is then as follows:

Firstly, an initial guess at the temperature distribution through the clothing system is made by setting Q_c, the liberation of heat due to condensation, and Q_R, the liberation of heat due to absorption of thermal radiation, to zero in equation 8:

$$(21)\quad \frac{d}{dx}\left\{k_H(x)\,\frac{dT(x)}{dx}\right\} = 0$$

Integrating twice and applying the boundary conditions,

$$T(D) = T_1 \text{ and } T(0) = T_0,$$

$$(22)\quad T(x) = T_0 - Q_0 \int_0^x dx'/k_H(x')$$

where $(23)\quad Q_o = (T_1 - T_0)/R_H$

with $(24)\quad R_H = \int_0^D dx/k_H(x)$

These are, of course, precisely the results one expects in the absence of any condensation or radiative heat transfer, with R_H being the total thermal resistance.

Secondly, the temperature calculated from equations 22 to 24 is used to calculate the rate of radiative heat absorption $Q_R(x)$, according to equation 11, and the saturation vapour pressure $P_s(x)$. From $P_s(x)$, the constraints of equation 20, and the boundary conditions on P, an initial estimate of P(x) is made. To calculate P(x), it is noted that equations 5 and 9 combine to give:

$$(25) \quad \frac{d}{dx} m(x) = -m_c(x)$$

Since the rate of condensation of water vapour $m_c(x)$ is always zero or positive in this study (no evaporation takes place), $\frac{d}{dx} m(x)$ must be either zero or negative and further only is non-zero where $P = P_s$. Thus the rate of flow of water vapour m(x) is constant in the regions where $P < P_s$ and monotonically decreasing where $P = P_s$. Where m(x) is a constant, the curve P(x) is a straight line and where m(x) is not constant, the curve follows the saturation vapour-pressure curve $P_s(x)$. These observations are sufficient to uniquely define P(x) for a given $P_s(x)$ and a given set of boundary conditions.

The type of curve obtained is illustrated in Figure 3. It is made up of a series of straight lines where $P(x) < P_s$ and curves where $P = P_s$ and so condensation occurs. There are abrupt changes of slope where the boundaries of each clothing layer, and hence discontinuities in vapour conductivity $k_V(x)$, occur. The rate of flow of water m(x) is continuous across these boundaries unless $P = P_s$, in which case condensation occurs, then m_c is non-zero and m(x) may be discontinuous. Such discontinuities in m(x) can be expected at the inside surface of an impermeable layer where condensation may occur right at the surface without condensation on either side. Once P(x) is known it may be differentiated according to equation 9 to give $m_c(x)$ and hence $Q_c(x)$ from equation 10. The third step in the solution is to put the calculated values of $Q_c(x)$ and $Q_R(x)$ into equation 8 and again integrate and apply the boundary conditions:

$$(25) \quad T(x) = T_0 - Q_0 \int_0^x \frac{dx'}{k_H(x')} - \int_0^x \frac{dx'}{k_H(x')} \int_0^x dx'' \left\{ Q_c(x'') + Q_R(x'') \right\}$$

where now

$$(26) \quad Q_0 = \frac{1}{R_H} \quad T_0 - T_1 - \int_0^D \frac{dx}{k_H(x)} \int_0^{x'} dx'' \quad Q_c(x'') + Q_R(x'')$$

and R_H is defined as before (equation 24).

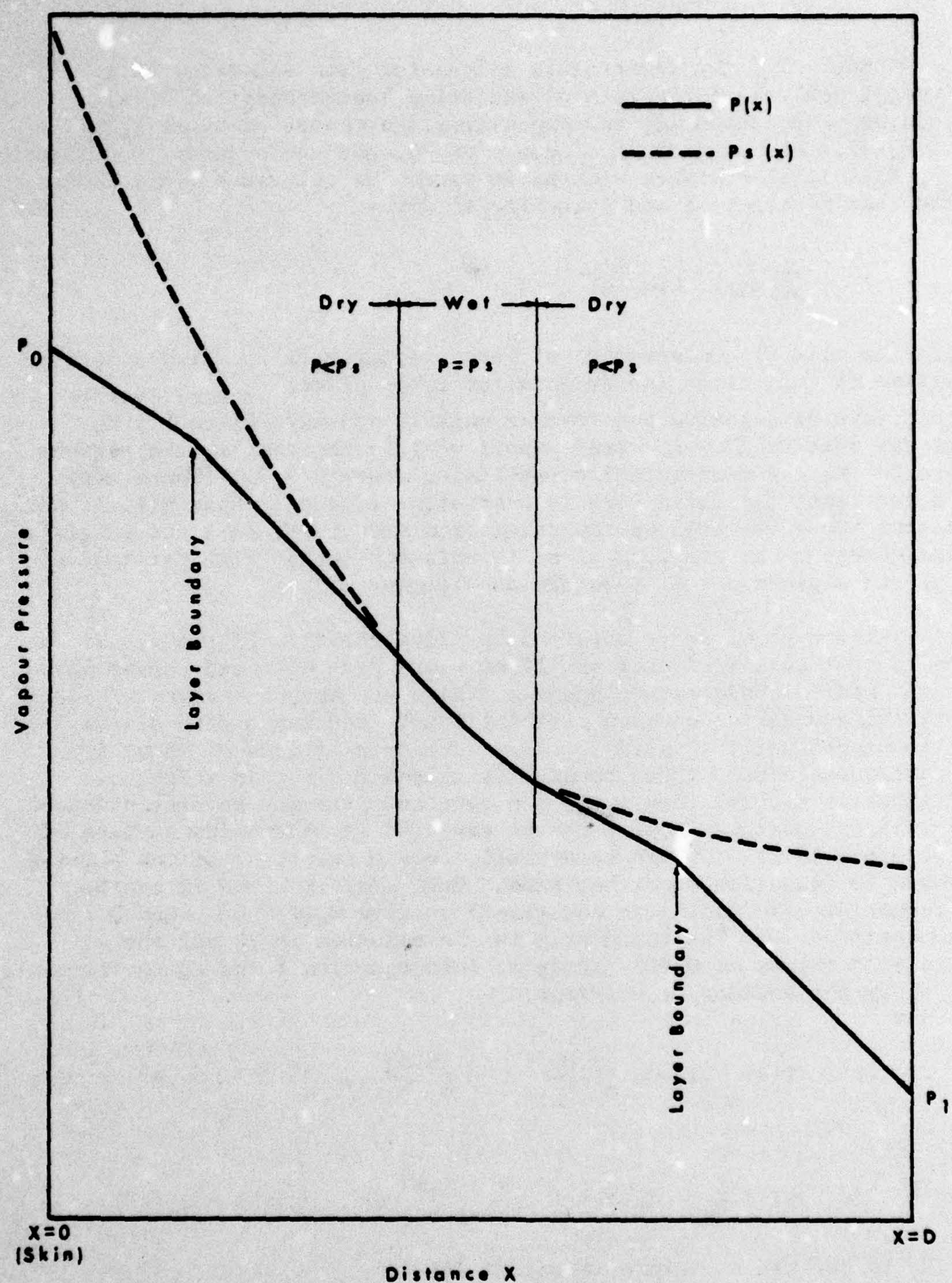

Figure 3. Illustration of the vapour pressure P and the saturation vapour pressure P_s as a function of position within a clothing system. P(x) is a set of straight lines, where $P < P_s$ and no condensation occurs, and curves, where P=Ps and condensation does take place. The slope of the line $P_s(x)$ is discontinuous at layer boundaries.

This new estimate of $T(x)$ is now used to recalculate Q_R, P_s, P and m_c and the solution proceeds iteratively.

In summary, the method of solution is:

(1) Assume no condensation
(2) Calculate T from: $\frac{d}{dx}\left\{k_H \frac{dT(x)}{dx}\right\} = 0$
(3) Calculate $Q_R(x)$
(4) Calculate $P(x)$ from
(i) $P(x) = P_s$ where condensation occurs.

(ii) $\frac{d}{dx}\left\{k_V \frac{dP(x)}{dx}\right\} = 0$ where no condensation occurs.

(5) Calculate

$$m_c(x) = \frac{d}{dx}\left\{k_V(x) \frac{dP(x)}{dx}\right\}$$

(6) Calculate

$$Q_c(x) = H\, m_c(x)$$

(7) Calculate a new $T(x)$ from:

$$\frac{d}{dx}\left\{k_H(x) \frac{dT}{dx}\right\} = - Q_c(x) - Q_R(x)$$

A computer program has been written in APL for a Xerox Sigma 9 computer to solve these basic equations with various types of boundary conditions and clothing layer systems. The program is interactive and can be operated by an individual researcher, regardless of previous computer experience, after a few minutes of instruction. The operator may define a clothing system by choosing layers from a catalogue of materials whose heat and vapour transport properties are known, define the boundary conditions, control the progress of the calculation and display the results in printed or graphic form. The iterative procedure converges rapidly enough to surpass the machine accuracy after about 30 iterations; normally about 6 iterations would be required so that $T(x)$, for example, is within 0.1°C (RMS) of the final solution.

PART II - CALCULATIONS FOR GORE-TEX* AND IMPERMEABLE RAINWEAR

INTRODUCTION

A situation in which the details of the heat and water-vapour transport within the layers of a clothing system greatly affect comfort is one in which the wearer of a rainsuit works sufficiently hard to promote sweating. Even if the rainwear is totally impermeable so that no water vapour can escape (except by forced convection through openings in the suit), the diffusion of water vapour from the skin to the impermeable layer can carry significant quantities of heat and must be included in calculations of the thermal properties of the suit. In the case of a rainsuit made of a material like Gore-tex, which is waterproof but permeable to water vapour, vapour can escape through it by diffusion carrying with it a certain amount of heat. The advantage of Gore-tex over impermeable materials cannot be assessed by simply considering the overall vapour resistance of the materials themselves; the condensation of vapour on their surfaces must be considered explicitly.

This part of the paper describes calculations of the heat and vapour transport through both types of suit when worn over light combat clothing. The results provide an estimate of the benefit that may be obtained from a Gore-tex rainsuit in the avoidance of heat stress and in keeping the inner clothing free from the accumulation of sweat.

It is intended that these calculations will be useful as a guide in setting realistic ambient conditions and work loads in the physiological evaluation of Gore-tex or similar rainwear.

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* Manufactured by W.L. Gore & Associates, Inc., Elkton, Maryland.

MODEL CLOTHING SYSTEM

The model assumed for the clothing system is illustrated in Figure 4. Next to the skin is an air layer 5 mm thick followed by a light combat shirt (2); another 5-mm air layer; the rainsuit, either permeable Gore-tex or an impermeable material; and a final air layer, 2.5 mm thick. The pertinent properties of these materials are summarized in Table 1. In many respects, the model is arbitrary but an attempt at realism has been made. The thickness of the inner air layers is typical of those found in real clothing systems (3); that of the outer air layer corresponds roughly to the thickness required to account for the observed insulation between a fabric layer and the ambient air at a wind speed of 1.3 m/s (a walking speed of 3 mph)(4). There is considerable disagreement as to the appropriate value of the thermal resistance of air in the thin layers between the clothing layers. The value adopted here is the lowest of those compiled in Reference 3, (1 clo/cm). This was chosen since an underestimate of the thermal resistance of air might partially compensate for the exclusion of convection from the calculations. The thermal resistance and vapour resistance of samples of Gore-tex and the combat shirt fabric were measured with apparatus described elsewhere (5)(6). A hypothetical waterproof material was assumed to have the same thickness and thermal resistance as Gore-tex but zero vapour permeability.

The calculations were carried out for two types of climatic conditions. First a situation was envisaged in which it was not raining but that the atmosphere was humid as it is just before or after a period of rain. Second it was assumed that it was actually raining so that the outer surface of the rainsuit was wet. In this case the outer still air layer was omitted since the rain can be expected to keep this outer surface at ambient temperature and 100% relative humidity.

RESULTS

Figure 5 shows the results of calculations of heat flow through the clothing assembly, under various conditions, as a function of temperature. Curves A to E are for a dry rainsuit including the outermost air layer. Curve F is for the raining situation without the outermost air layer.

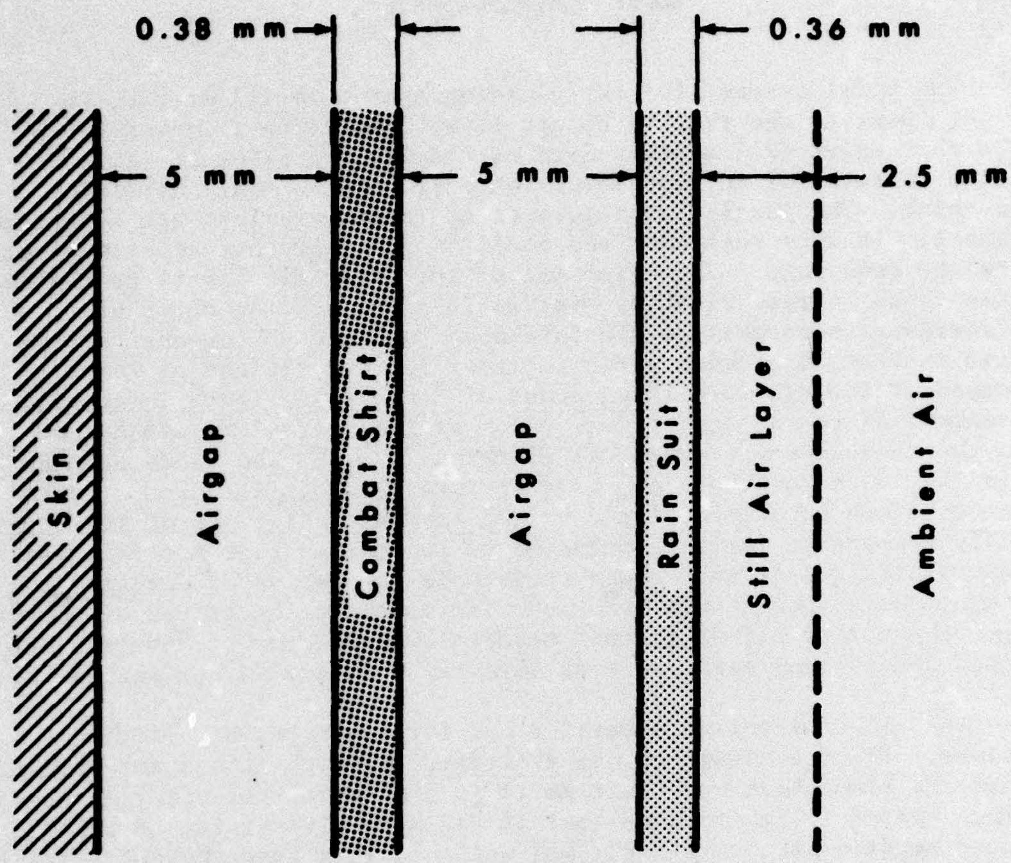

Figure 4. The model clothing system taken for the rainsuit calculations. The combat shirt and rainsuit are opaque. The outermost still air layer is appropriate to a walking speed of 1.3 m/s. The rainsuit is either totally impermeable or the permeable laminate Gore-tex.

TABLE I

Material Properties Used in the Calculations for the Rainsuits

Material	Thermal Cond. k_H (w/m K)	Vapour Cond. k_V (kg/s m pa)	Infrared Properties
Air	.064	1.8×10^{-10}	Transparent
Combat Shirt	.076	9.0×10^{-11}	Opaque
Gore-tex	.076	2.0×10^{-11}	Opaque
Waterproof	.076	0	Opaque

Curve A is the total conductive and radiative heat flow in the absence of any sweating or insensible perspiration. It is very close to a straight line since conductive heat loss is linear in temperature difference ($T_1 - T_0$) and radiative heat is nearly linear at these small temperature differences. For this curve, the slope can be interpreted as the reciprocal of a thermal resistance. At any ambient temperature and a skin temperature of 35°C the body will be in thermal balance at a heat production rate given by Curve A. If the heat production is less than this, cold stress will ensue; if more, heat stress will ensue unless sweating occurs.

Curve B is a calculation for a rainsuit that is totally impermeable and for a subject who is sweating fast enough to keep the skin wet i.e. at 100% RH. Thus, at any temperature, curve B gives the maximum quantity of heat that can pass through the clothing system including transfer by conduction, radiation and evaporation of sweat from the skin. In the region between Curves A and B thermal balance is possible if the body regulates the production of sweat appropriately.

Curves C, D, and E are for a subject who is profusely sweating, as in Curve B, but for a Gore-tex rainsuit under conditions of, respectively, 100, 75 and 50% ambient RH and similarly define regions of possible thermal balance. These curves indicate under what conditions thermal stress will be experienced.

For example, if the ambient temperature is 20°C and it is not raining, then a subject, wearing an impermeable rainsuit, will suffer cold stress if his heat output is less than 103 w/m^2, will be able to maintain heat balance for outputs from 102 w/m^2 to 171 w/m^2 by sweating and will suffer heat stress at heat production rates above 171 w/m^2. For a Gore-tex suit this upper bound is extended to 194 w/m^2 for 100% RH, 206 w/m^2 at 75% RH and 221 w/m^2 at 50% RH, improvements of 23, 35 and 50 w/m^2 respectively. Since a man walking at 1.3 m/s (3 mph) produces about 180 w/m these differences could be significant, but this calculation probably overestimates rather than underestimates the advantage of Gore-tex. This is because pumping of air in and out of the suit is neglected.

In the case where the rainsuit is actually wet the difference between Gore-tex and impermeable rainwear is only about 1 w/m^2 and insignificant (Curve F for both fabrics). This is not surprising since, as the outside surface of the Gore-tex is at 100% RH, in order to obtain significant vapour flow the inside surface must be at or near 100% RH at a higher temperature. As the thermal resistance of the Gore-tex is low the temperature drop across it will be low and little vapour flow will result.

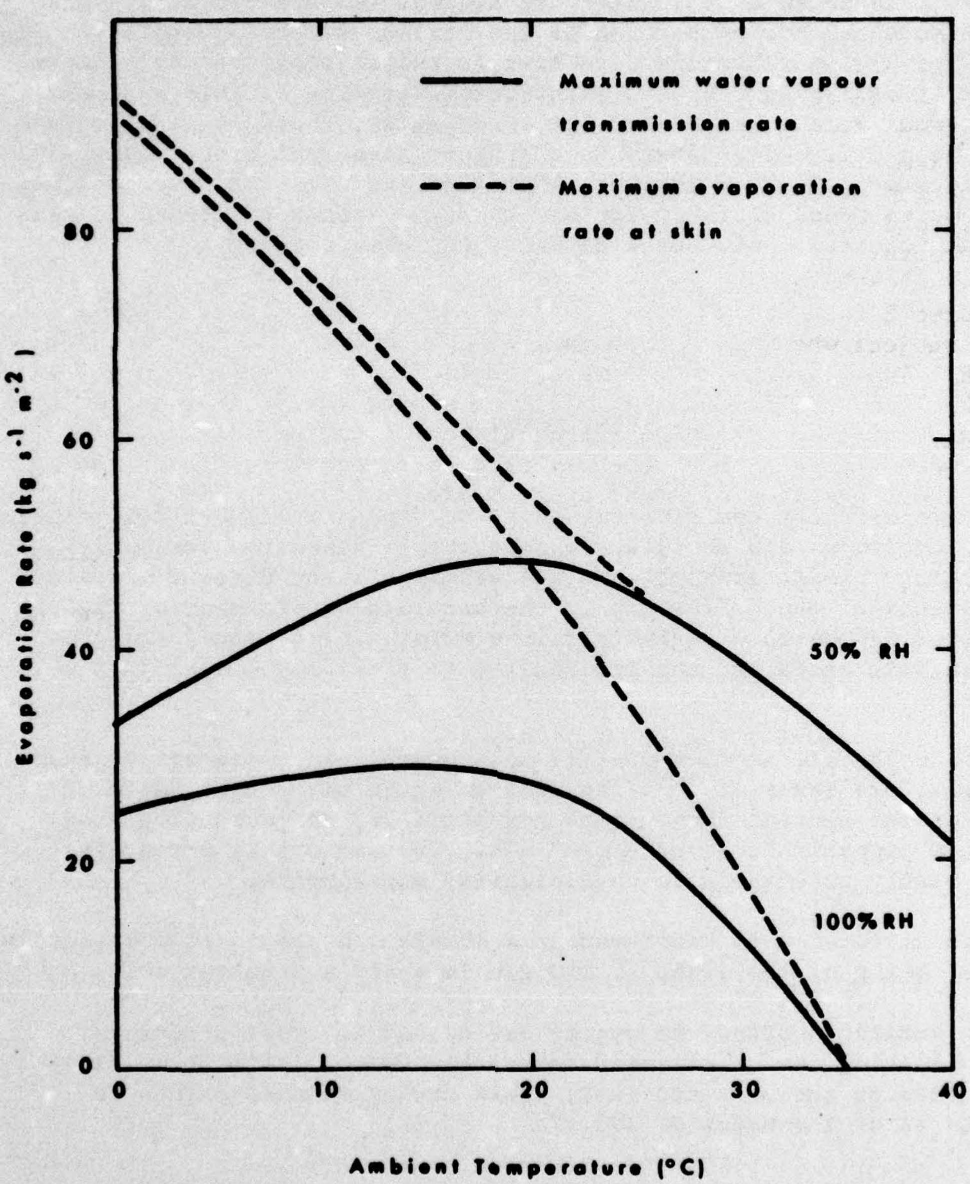

Figure 6. The maximum rate at which water vapour can escape from a Gore-tex rainsuit for varying ambient temperature. Also shown, for comparison, is the maximum rate at which sweat can evaporate from the skin. A significant fraction of the evaporated sweat can escape.

In Figure 6 the maximum transmission of water vapour through a Gore-tex suit is shown as a function of ambient temperature at 100 and 50% RH. Also shown for comparison is the maximum rate of evaporation of sweat from the body that is effective in maintaining thermal balance. The vapour transmission can be a significant fraction of this maximum effective sweat-rate. Hence, for low sweat rates, there is a definite advantage to a Gore-suit. There is a further advantage since water will continue to evaporate from the wet inner clothing after the sweating has ceased, and the inner clothing can dry as water vapour continues to pass through the Gore-tex. Of course no water can escape through the impermeable rainwear.

CONCLUSION

These calculations give the heat and vapour transport for rather idealized conditions and therefore should not be taken too seriously with respect to predictions of absolute values of heat stress. However the predictions of the difference in the heat stress produced by the two types of suit may be more reliable, since errors in the model will be the same in both cases and can be expected to partially cancel in the difference.

The calculations then predict an advantage in avoidance of heat stress for a Gore-tex suit of a few tens of watts per square metre depending on the ambient temperature and humidity. A measurable heat stress would probably be about $10\,w/m^2$ (7). Therefore this advantage should be easily observable in physiological experiments.

The difference in water-vapour accumulation should also be easily observable, being of the order of 100 g/h less for a Gore-tex suit.

In addition, after the wearer has ceased to sweat profusely, the inner clothing can be expected to dry because of continued diffusion of vapour through the Gore-tex suit. This drying rate can again be expected to be of the order of 100 g/h.

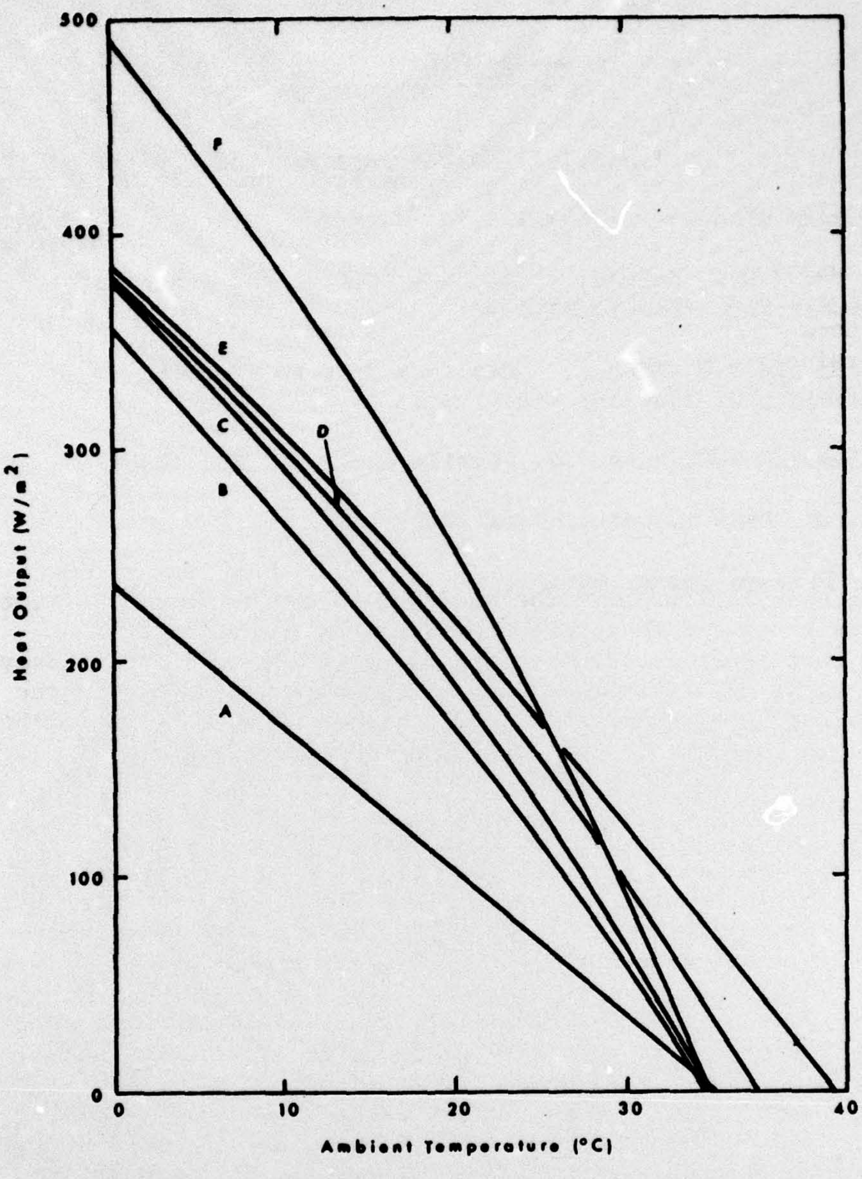

Figure 5. The total conductive evaporative and radiative heat loss through a rainsuit as a function of ambient air temperature for:

A No sweating
B Maximum sweating, impermeable suit
C Maximum sweating, Goretex suit, 100% RH
D Maximum sweating, Groetex suit, 75% RH
E Maximum sweating, Goretex suit, 50% RH
F Maximum sweating, either suit totally wet.

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A numerical model has been developed to calculate the combined heat and vapour flow, at steady state, through multilayer clothing systems including heat transfer by radiation and the condensation of water vapour within the clothing system. The model has been applied to a comparison of the heat stress and water accumulation expected in rainwear made of completely impermeable material and of a water-vapour-permeable laminate, when the wearer works hard enough to promote sweating. The results indicate significant advantages can be expected from the permeable rainsuit.

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